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# Capacitors placement by NSGA-II in distribution systems with non-linear loads

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ABSTRACT

The research in methodologies for capacitor placement in primary distribution circuits is a recurrent topic in the specialized bibliography. Most of the presented formulations consider the minimization of the energy losses and the peak power losses of the circuit as well as the cost of the capacitors. However have been considered some additional objectives like: minimum deviation of voltage. Only few of the methods presented are able to determine the frontier of Pareto of the multi-objective optimization problem, while the rest of the contributions use just a single function objective that includes all the objectives by means of factors of weight. Besides, most of the contributions are applied to circuits balanced with linear load. In the present work develops a method to determine the number, placement, control and size of the fixed and switched capacitor banks in primary distribution circuits contaminated by harmonics. The necessary power quality constraints and of overstress of the capacitors are used. The developed program is based on the multi-objective optimization algorithm NSGA-II. The effectiveness of the proposed procedure is tested by solving a practical example.



## Introduction

The research in methodologies for capacitor placement in primary distribution circuits is a recurrent topic in the specialized bibliography. Diverse methods of optimization have been employees with this objective from the year 2000 so far. Efficient heuristic algorithms based on indicators of sensibility of the function objective [1,2], the mixed-integer method of linear programming [3,4], diverse types of genetic algorithms [5–15], the particle swarm optimization method [16–18] and other search algorithms [19–23] have been applied to solve this problem.

Most of the presented formulations [1,5,6,8–10,16–20,23–28] consider the minimization of the energy losses and the peak power losses of the circuit as well as the annual cost of the capacitors. However, the use of the project evaluation technique of the Net Present Value (NPV) [3,18] improves the economic evaluation of the compensation project by capacitors.

The methods in [1] do solve the compensation by placing and selecting the capacitors one by one, not considering the interrelation between the several capacitors localization and size. The method in [2] improves the selection of the capacitor sizes by solving a linear equations system.

In [3,4] is developed a linear model to solve the compensation problem, however, this type of model cannot solve the systems contaminated by harmonics.

The methods presented in [4,7,11–15,21,22,28] consider additional objectives like: minimum deviation of voltage. Some of them mixing the capacitors placement problem with other related problems such as: voltage regulators settings [4,13], placement of distributed generation [15], load tap-changer settings [18], and improvement of stability index [22,28].

Only some of the methods [4,7,14,28] are able to determine the frontier of Pareto of the problem, while the rest of the contributions uses just a single function objective that includes all the objectives by means of factors of weight. The obtaining of this frontier is important in order to show the compromise between the

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various objectives and the selection of several optimal solutions for the problem, with different impact on the persecuted goals.

Most of the contributions are applied to circuits balanced with linear load, while the methods presented in [8,14,16,26] are applied to circuits contaminated by harmonics. In these contributions there are used additional power quality constraints.

The objective of contributions [8,16,26] is minimize the annual circuit cost by using capacitor banks of fixed type. Only a constraint of maximum total harmonic distortion is employed in these formulations.

The contribution [14] includes the fixed and switched capacitor banks and employs constraints to comply with all the recommendations of the IEEE Std. 519 [29] as well as to avoid the overstress of the used capacitors. However, it is discussable the objective of least squares of the increments of harmonic voltages in [14], because a high increment of distortion in one node can remain undetected if in other nodes the distortion is decreased. Besides, this objective tries to maintain the same previous distortion instead of try to decreasing it.

In the presented work develops a method to determine the number, placement, control and size of the fixed and switched capacitor banks in primary distribution circuits contaminated by harmonics that improves the previous contributions. The multi-objective formulation allows the solving of the problem with the necessary power quality constraints and of overstress of the capacitors. The developed application is based on the algorithm NSGA-II that allows the obtaining of the frontier of Pareto of the optimization problem. The effectiveness of the proposed procedure is tested by solving a practical example.

## Problem formulation

In the present work formulates the capacitor placement problem in harmonic polluted distribution circuits as a multi-objective optimization problem that pursues the selection and placement of the needed capacitors to obtain: the maximum Net Present Value (NPV) of the compensation project, the minimum deviation of voltage ($\Delta V$), and the minimum Total Harmonic Distortion (THD) of voltage. The solutions are subject to comply with the constraints of: power quality and of overstress of the capacitors

*Independent variables*

The independent variables of the problem, represented by the array $x$, are: the number of capacitor banks ($n$) and their placements ($u_1,\ldots,u_n$), their controls ($c_1,\ldots,c_n$) and their sizes ($Qc_1,\ldots,Qc_n$).

The possible placements are the nodes of the circuit. The controls express if the bank is of fixed-type ($c_i = 1$) and if the bank is of switched-type (the bank is connected in the load states $\leqslant c_i$). The sizes are multiples of the desired capacitor units. All the variables are integer-type.

*Objective functions*

The presented optimization problem can be formalized by means of three objective functions: the maximization of NPV of the compensation project, the minimization of the maximum voltage deviation and the minimization of the maximum THD of voltage.

*NPV of the project*

As the installation of capacitors in a circuit is in definitive an investment project that pursues to obtain earnings starting from the economy achieved in the cost of operation of the network, it can be used the NPV like an economic indicator that gathers in a single function, the investment costs and of operation of the electric network.

Considering a period of evaluation of $Y$ years with a reason of interest $i$, the NPV of the compensation project is calculated as:

$$\mathrm{NPV}(x) = -I(x) + \sum_{k=1}^{Y}(C(0) - C(x))/(1+i)^k \tag{1}$$

where $I(x)$ is the investment cost of the capacitors, composed by:

$$I(x) = \sum_{i=1}^{n}(Kc_i \cdot Qc_i + Kcf_i) \tag{2}$$

where $Kc_i$(\$/kvar) and $Ccf_i$(\$) are: the cost per kvar installed and the fixed cost of the capacitor bank of size $Qc_i$. Besides, $C(0)$ represents the cost of operation of the circuit in the base case (uncompensated) and $C(x)$ the cost obtained after the installation in the network of the capacitors represented by $x$.

$$C(x) = cd \cdot \Delta P_{\max}(x) + \sum_{k=1}^{L} ce_k \Delta P_k(x) \cdot \Delta t_k \tag{3}$$

where $cd$ (\$/kW) and $ce_k$ (\$/kW h) are the corresponding cost coefficients for the peak power losses and the energy losses in the load level $k$.

*Maximum voltage deviation function*

The maximum deviation of voltage is defined as the difference between the maximum and the minimum voltage, considering the set $U$ of all the system nodes and the set $L$ of all the load levels.

$$\max \Delta V(x) = \max_{\substack{k\in L\\ i\in U}}\{V_{k,i}(x)\} - \min_{\substack{k\in L\\ i\in U}}\{V_{k,i}(x)\} \tag{4}$$

By reducing the maximum deviation of voltage, the optimization process improves the voltage conditions in all system nodes and for all the load levels.

*Function of maximum THD of voltage*

The capacitors are reactive power compensators. However, the same ones can magnify the effects of harmonics of the loads due to the existence of resonances with the inductive elements of the electric network.

Nevertheless, the effect of the capacitors over the voltage depends on the size and placement of the same ones in the circuit. Due to this, it can be found a solution based on the use of capacitors that doesn't increase the indicators of distortion or that it even reduces them.

In this formulation, it is defined as a third objective the minimization of the maximum THD of voltage in the set $U$ of the system nodes, and the set $L$ of all the considered load states.

$$\max \mathrm{THD}(x) = \max_{\substack{k\in L\\ i\in U}}\{\mathrm{THD}_{k,i}(x)\} \tag{5}$$

The THD of voltage is one of the principal indexes of distortion considered by standards like the IEEE Std. 519. Trying to reduce the maximum THD, the optimization process improves the harmonic distortion indexes of voltage of the system nodes, facilitates compliance of the power quality standards and allows the finding of solutions with lower distortion indexes than the recommendations of the standards.

Therefore, the problem of optimization can be formalized as:

$$\min \begin{cases} f_1(x) = -\mathrm{NPV}(x) \\ f_2(x) = \max \Delta V(x) \\ f_3(x) = \max \mathrm{THD}(x) \end{cases} \tag{6}$$

It should be observed that the minimization of $-\mathrm{NPV}(x)$ is equivalent to the maximization of $\mathrm{NPV}(x)$.